Studies of exclusive production of η' and $f_1(1285)$ mesons in $p+p$ collisions at 4.5 GeV with HADES@FAIR/GSI

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Physics Motivations: η' and $f_1(1285)$ mesons

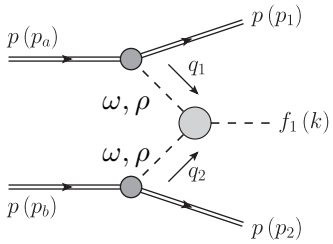
Production Mechanisms: Investigate inclusive cross sections at low energies to test effective Lagrangian approaches.
recorded at pp at $\sqrt{s} = 12.7$ and 29.1 GeV (WA102 collaboration);
in photoproduction γp at $\sqrt{s} \leq 2.8$ GeV (CLAS).

Nature of $f_1(1285)$: explore its production as an "exotic state" via vector-vector (VV) fusion near the threshold ($\sqrt{s} = 3.46$ GeV):
The $\omega\omega \to f_1$ and $\rho\rho \to f_1$ fusion are the most probable low energy production processes.

Impact on $(g-2)_\mu$: Assess couplings to photons to constrain uncertain Light-by-Light (LbL) scattering contributions (e.g., $\gamma^*\gamma^* \to f_1(1285)$) for anomalous magnetic moment calculations

Decay Dynamics & Form Factors: Analyze Dalitz plot parameters and transition form factors in various decay channels

η' production & structure: crucial to probe the structure; also acts as a "standard candle" to calibrate f_1 production ($\sigma(pp \to pp\eta') \approx 3$ μb@4.5 GeV based on DISTO measurement) – shares the same $\eta\pi^+\pi^-$ decay channel



The focus is to study exclusive production of f_1 and η' in the decay channel $pp \to ppf_1/\eta'(\to \eta[\to \pi^+\pi^-\pi^0]\pi^+\pi^-)$, looking for 6-tracks event topology.

$pp \to ppX$ reactions

Signal/Background channels	Estimated cross section (μb)	Reference/Comments
$f_1[\eta[\to \pi^+\pi^-\pi^0]\pi^+\pi^-]$	0.012	[1]
$\eta'[\eta[\to \pi^+\pi^-\pi^0]\pi^+\pi^-]$	0.3	[1,2]
$2\pi^+2\pi^-\pi^0$	88	[3]
$\eta[\to \pi^+\pi^-\pi^0]\pi^+\pi^-$	0.18	[1] (?)
$\omega[\to \pi^+\pi^-\pi^0]\pi^+\pi^-$	80	[5]

[1] P. Lebiedowicz et al., PRD 104, 034031 (2021)
[2] P. Moskal et al., IJMPA 22:305-316 (2007)
[3] G. Alexander, PR 154, 1284 (1967)
[5] $\sigma = 0.09 \pm 0.03$ mb for $pp \to pp\pi^+\pi^-\omega$ at $p_{\text{lab}} = 6.92$ GeV/c; BR$(\omega \to \pi^+\pi^-\pi^0) = 0.89$

Cross section estimations: signal

$pp \to pp\eta'$:

$\sigma(pp \to pp\eta') = 2.28 - 2.69$ μb.
From effective Langrangian $\{\pi, \rho, \eta\}NN^*$ couplings
P. Lebiedowicz, Workshop 1GeV Scale (2024)

$pp \to pp\eta'$: fit to data

For $\sqrt{s} = 3459$ MeV, excess energy is $Q = \sqrt{s} - (2m_p + m_{\eta'}) = 625$ MeV,
Faldt and Wilkin parametrization [1]:

$$\sigma_{pp\to pp\eta'}(Q) = C\frac{Q^2}{m_p p_{\text{lab}}}\left(1+\sqrt{1+Q/\epsilon}\right)^{-2},$$

where $C = 42 \pm 7$ mb, $\epsilon = 0.62 \pm 0.13$ MeV from fit to DISTO data [2]
$\sigma(pp \to pp\eta') = 3.04$ μb
$\sigma(pp \to pp\eta'(\to \pi^+\pi^-\eta[\to \pi^+\pi^-\pi^0])) = 0.3 \pm 0.06$ μb

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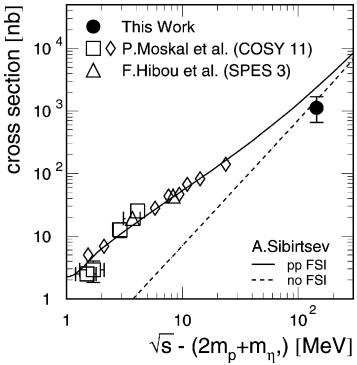
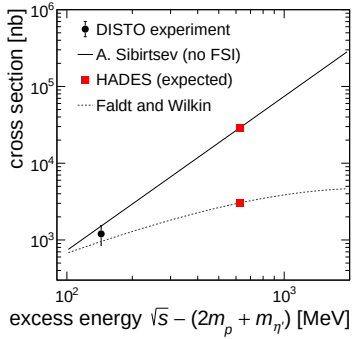
[1] G. Faeldt and C. Wilkin PLB 382 (1996) 209–213
[2] P. Moskal et al., IJMPA 22, 305 (2007)
[3] A. Sibirtsev and W. Cassing, EPJ A, 2 4 (1998) 333-335





Cross section estimations: background

$pp \to pp2\pi^+2\pi^-\pi^0$:

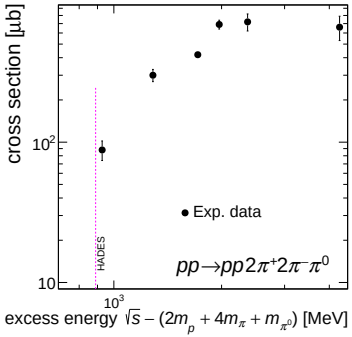
88 ± 14 μb at $p_{\text{lab}} = 5.5$ GeV/c (see plot)
G. Alexander, PR 154, 1284 (1967)

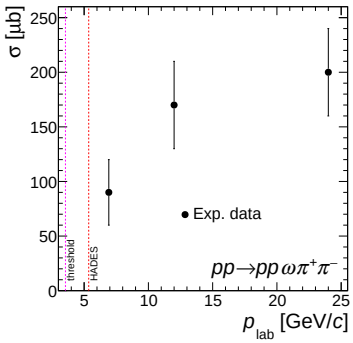
$pp \to pp\omega\pi^+\pi^-$ (μb):

90 ± 30 at $p = 6.92$ GeV/c
170 ± 40 at $p = 12$ GeV/c
200 ± 40 at $p = 24$ GeV/c
$\text{BR}(\omega \to \pi^+\pi^-\pi^0) = 0.89$
$\Rightarrow p_{\text{lab}} = 5.356$ GeV estimate: $90 \cdot 0.89 = 80$ μb

$pp \to pp\eta\pi^+\pi^-$:

$\sigma(pp \to pp\eta(\to \pi^+\pi^-\pi^0)\pi^+\pi^-) = 0.18$ μb
estimates via two $N(1440), N(1535)$ resonances
PRD 104, 034031 (2021)





HADES $p_{\text{lab}} = 5.356$ GeV

$pp \to ppX$ reactions: expected statistics at HADES

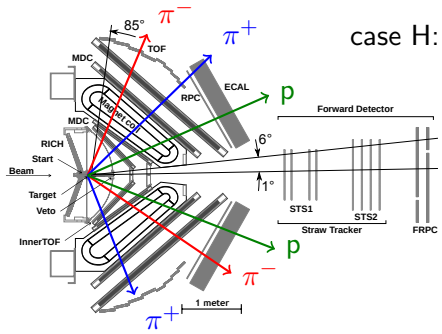
Number of expected counts: $N = \mathcal{L} \cdot \sigma \cdot \epsilon$
Integrated luminosity pp@4.5 GeV of HADES data in 2022:
$\mathcal{L} = 5660.6 \pm 0.1$ (stat.) ± 226.0(norm.) ± 180.0(syst.) nb^{-1}
Expected statistics at HADES (upper limit) using PLUTO simulations:

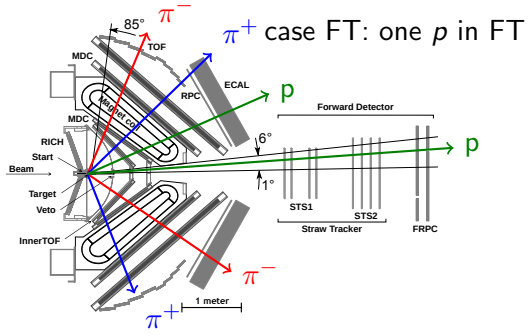
Signal/Background channels	Estimated σ (μb)	Sim. Rec. Eff.	No. Evts HADES	FT Sim. Rec. Eff.	No. Evts FT
$f_1[\eta[\to \pi^+\pi^-\pi^0]\pi^+\pi^-]$	0.012	1.55e-4	**10**	1.23e-3	**80**
$\eta'[\eta[\to \pi^+\pi^-\pi^0]\pi^+\pi^-]$	0.3	6.16e-4	**1030**	1.13e-3	**1900**
$2\pi^+2\pi^-\pi^0$	88	1.7e-4	67800	1.e-3	400000
$\eta[\to \pi^+\pi^-\pi^0]\pi^+\pi^-$	0.18	2.81e-4	280	1.1e-3	1100
$\omega[\to \pi^+\pi^-\pi^0]\pi^+\pi^-$	80	1.23e-4	27900	1.1e-3	248000

$^{(*)}$ (In preparation) HADES Collaboration, *Measurement of Differential Cross Sections and Integrated Luminosity using Proton-Proton Elastic Scattering with HADES at $T = 4.53$ GeV, $T = 1.60$ GeV*
If channel is mentioned with decay mode, *e.g.* $\eta[\to \pi^+\pi^-\pi^0]$, the branching ratio factor is included

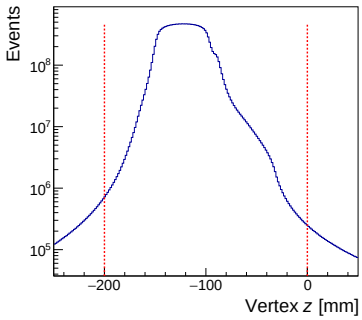
Setup, cuts, details

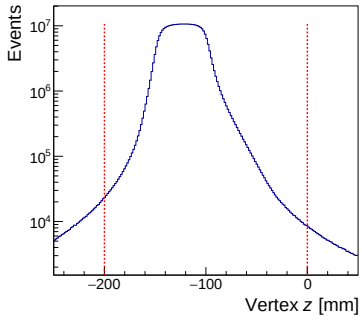
- pp@4.5 GeV ($\sqrt{s} = 3.46$ GeV) gen4 dataset (PT3 trigger)
- Main vertex $z \in (-200, 0)$ mm
- Start detector: hit
- HADES tracks: `kIsUsed`, not `kIsLepton`; Mag. field & dEdx momentum correction (after β cut)
- FT: `kIsUsed`
- PID based on $\pm 2.5\sigma$ cut on β–momentum (Witold P.)
- $2p$, $2\pi^+$, $2\pi^-$ particles
- $2p$, $\geq 2\pi^+$, $\geq 2\pi^-$ particles, set of $2\pi^+2\pi^-$ selected with minimum product of (χ^2) of contributing tracks: $\min \prod_{i=1}^{4} (\chi^2_{RK})_i$
- Kinematic Fit constraints: missing π^0 mass and total momentum; track parameter resolution map from S. Trelinski

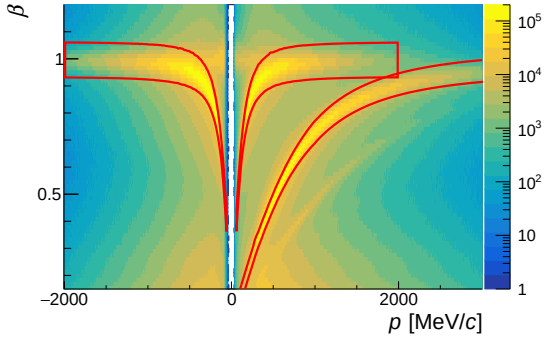


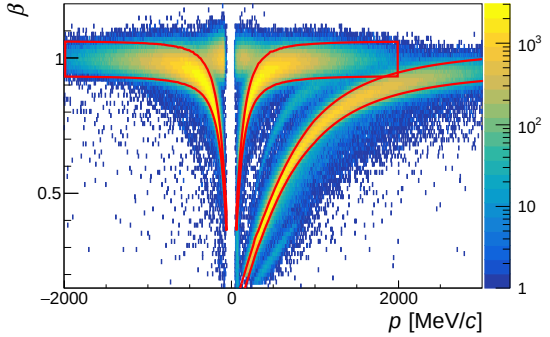


Vertex and PID cut: data (*top*) and MC (*bottom*)



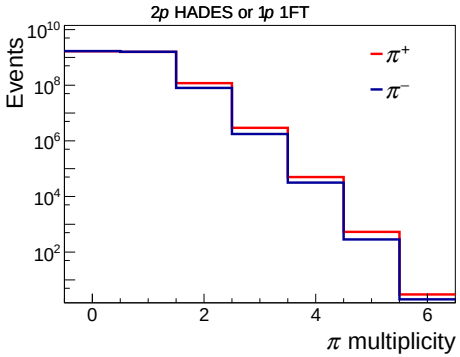


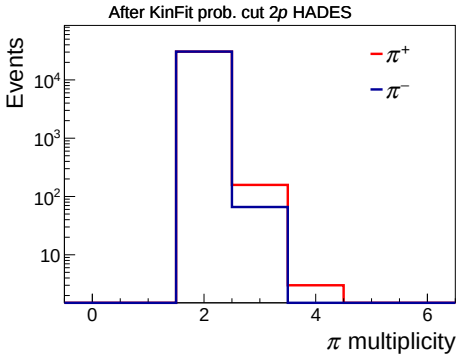


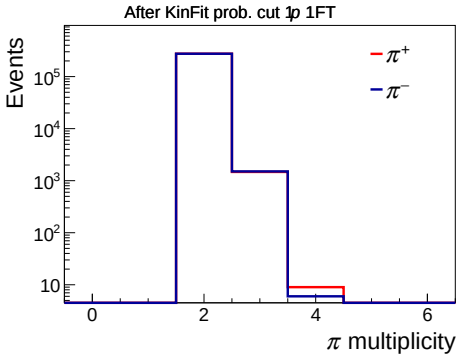


Pion multiplicity in studied events

Multiplicities of $\pi^{\pm}$:





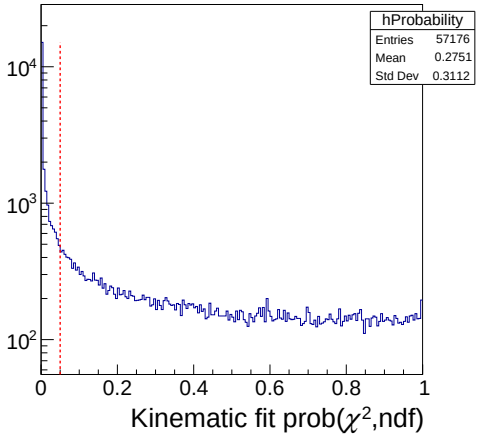


Selected events for analysis after all cuts (after successful KinFit) consists dominantly of events with $2\pi^+2\pi^-$

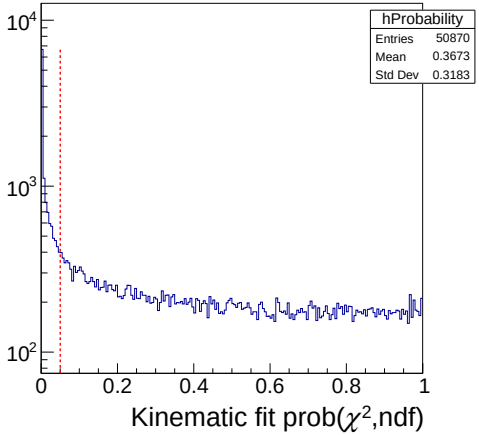
KinFit - missing π^0 mass

Kinematic Fit constraints: missing π^0 mass; total momentum

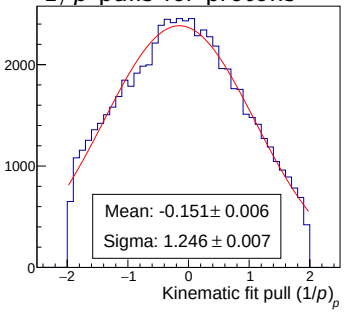
data



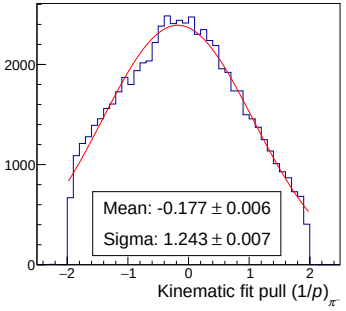
f_1 signal MC



$1/p$ pulls for protons



$1/p$ pulls for π^-s

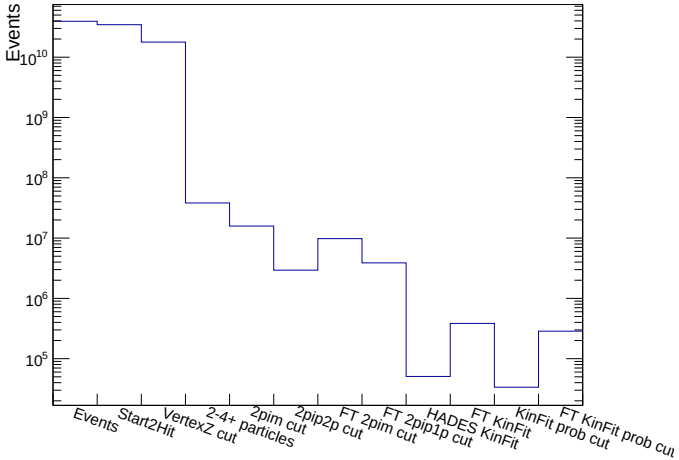


Cut was implemented for values $p < 0.05$ – removes bad fits

Pulls distributions for data after this cut - see *right*

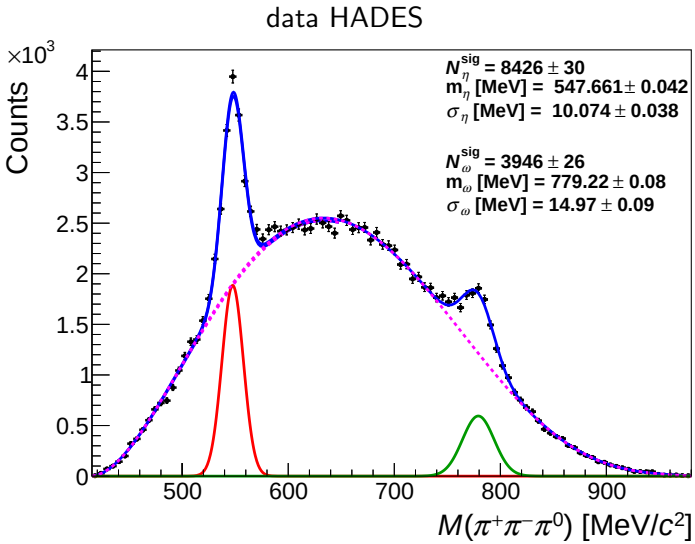
Track resolution: map from S. Trelinski

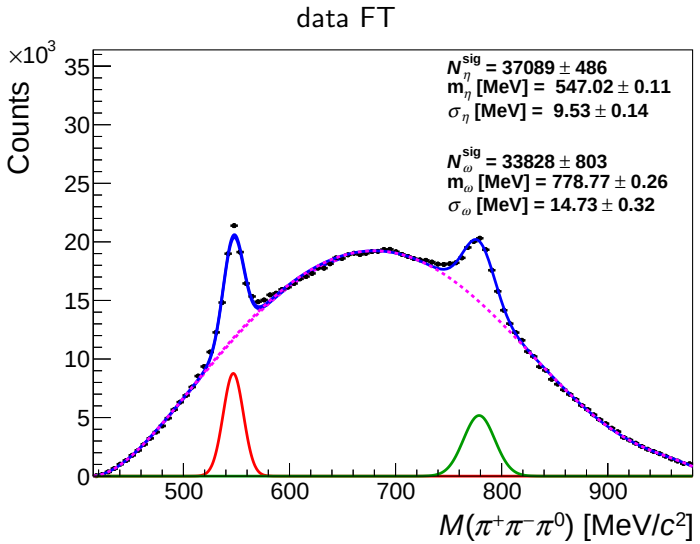
Event cut flow



Cut	HADES	FT
Total Events	3.94e+10	
Start detector	3.46e+10	
VertexZ cut	1.78e+10	
2- 4+ `kIsUsed` tracks	3.82e+07	
2- 3+ 1FT `kIsUsed` tracks		8.73e+07
(β, p) $2\pi^-$ cut	1.58e+07	9.79e+06
(β, p) $2\pi^+2p$ cut	2.94e+06	
(β, p) $2\pi^+1p$ cut		3.88e+06
KinFit converged	50742	384581
KinFit prob. cut	33624	285978
$m_{\text{inv}} \in (m_\eta \pm 30)$ MeV	17405	106504

Invariant mass $\pi^+\pi^-\pi^0$: HADES vs FT data





The tracker gives 4x events with η and 10x with ω!

Signal: gaussian, background: 9 order polynomial

RooFit: Extended Maximum-Likelihood binned fit

$pp \to ppX$ reactions: Sim PLUTO channels scaling

Number of expected counts: $N = \mathcal{L} \cdot \sigma \cdot \epsilon$
Integrated luminosity pp@4.5 GeV of HADES data in 2022: $\mathcal{L} = 5661 \pm 290$ nb^{-1}
For PLUTO datasets, $N^{\text{evts}} \approx 10^8$, so MC scaling factor $\mathcal{L} \cdot \sigma / N^{\text{evts}}$
Sim PLUTO channels scaling:

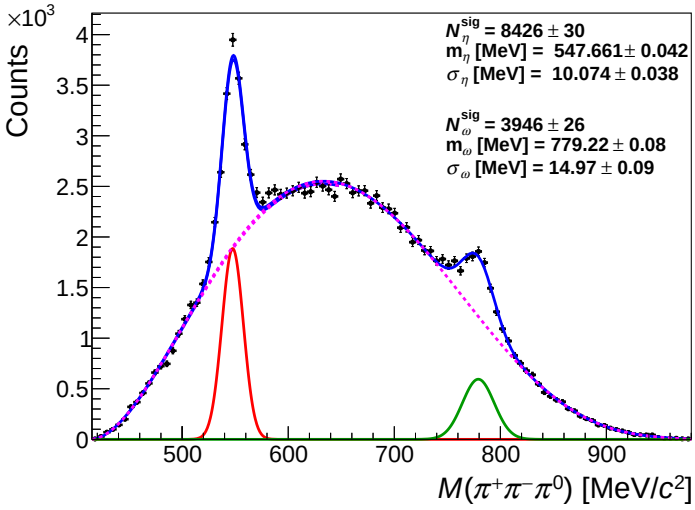
PLUTO ch no.	Signal/Background channels	Estimated σ (μb)	N evts	H Sim. events Reconstructed	FT Sim. events Reconstructed ($\times 10^3$)	$\mathcal{L}\sigma/N^{\text{evts}}$
950	$f_1[\eta[\to \pi^+\pi^-\pi^0]\pi^+\pi^-]$	0.012	98M	15190	121	7e-4
931	$\eta'[\eta[\to \pi^+\pi^-\pi^0]\pi^+\pi^-]$	0.3	100M	61618	114	0.017
11	$2\pi^+2\pi^-\pi^0$	88	47M	8150	48	8.32
925	$\eta[\to \pi^+\pi^-\pi^0]\pi^+\pi^-$	0.18	96M	27023	105	0.01
913	$\omega[\to \pi^+\pi^-\pi^0]\pi^+\pi^-$	80	94M	11621	103	2.40

SMASH$^{(\dagger)}$: $\sigma(pp \to pp\eta\pi^+\pi^-) = 42.2$ μb; $\Rightarrow \sigma(pp \to pp\eta[\to \pi^+\pi^-\pi^0]\pi^+\pi^-) = 9.7$ μb;
$\sigma(pp \to pp\omega\pi^+\pi^-) = 0.05$ μb.

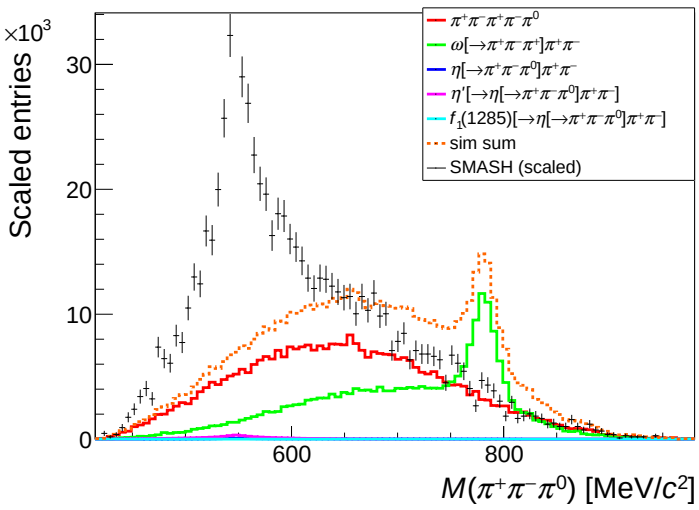
$^{(*)}$ (In preparation) HADES Collaboration, *Measurement of Differential Cross Sections and Integrated Luminosity using Proton-Proton Elastic Scattering with HADES at $T = 4.53$ GeV, $T = 1.60$ GeV*
If channel is mentioned with decay mode, *e.g.* $\eta[\to \pi^+\pi^-\pi^0]$, the branching ratio factor is included
$^{(\dagger)}$ Based on pp total inelastic cross section = 28.1 mb

Invariant mass $\pi^+\pi^-\pi^0$: HADES data vs sim

data



sim

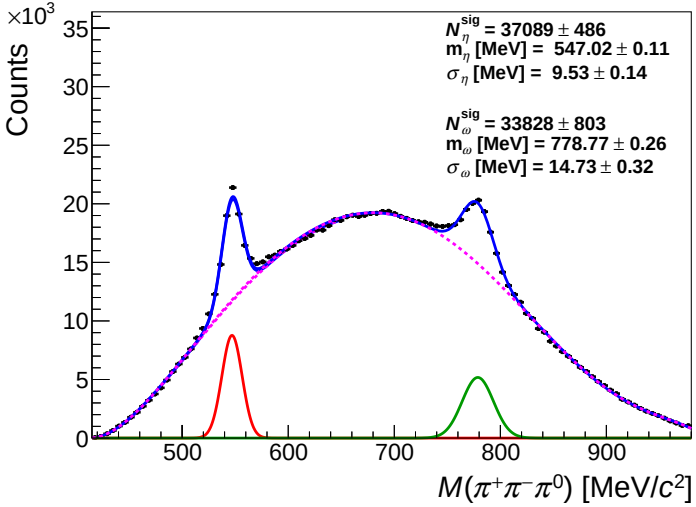


The η/ω peaks are nicely visible, but η/ω ratio is different in SMASH, data, and PLUTO (based on estimated σ)

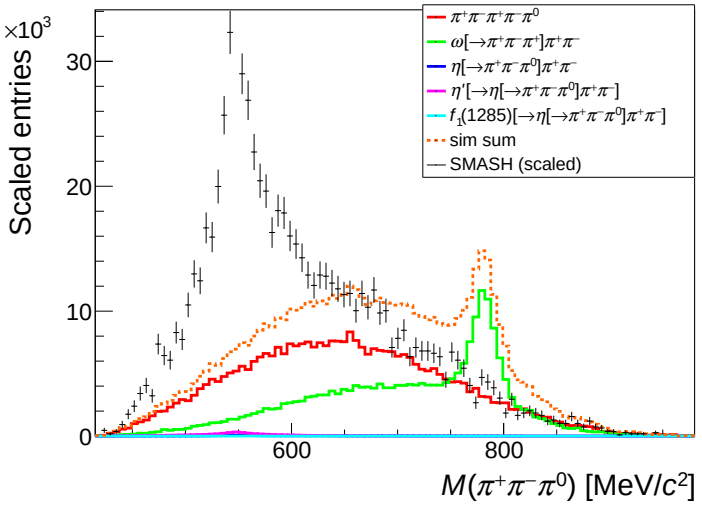
Sim pluto channels, scaled $\mathcal{L} \cdot \sigma / N^{evts}$

Invariant mass $\pi^+\pi^-\pi^0$: FT data vs sim

data FT



sim FT

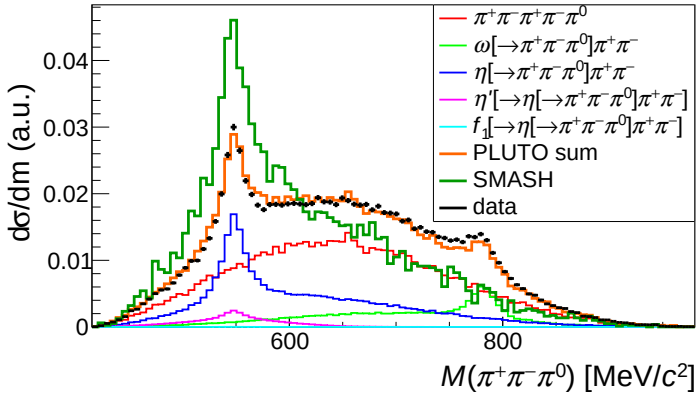


used cross sections: $\eta\pi^+\pi^-$: 5.57 μb, $\omega\pi^+\pi^-$: 5.57 μb (from my analysis)
$2\pi^+2\pi^-\pi^0$: 20 μb, $\eta'(\rightarrow \eta\pi^+\pi^-)$: 0.3 μb, $f_1(\rightarrow \eta\pi^+\pi^-)$: 0.012 μb

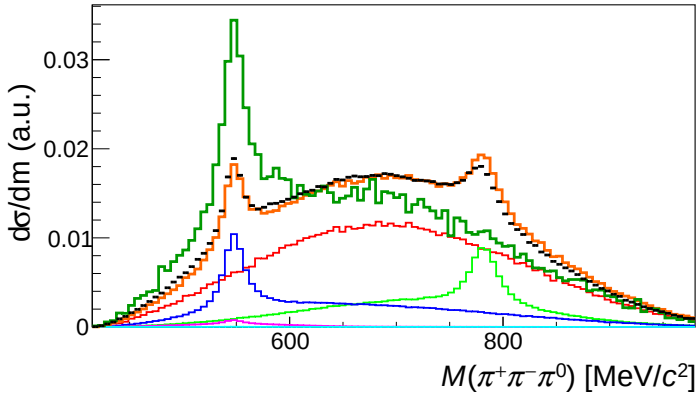
Sim pluto chanels, scaled $\mathcal{L} \cdot \sigma / N^{\text{evts}}$

Invariant mass $\pi^+\pi^-\pi^0$: data vs sim

data-sim



sim FT



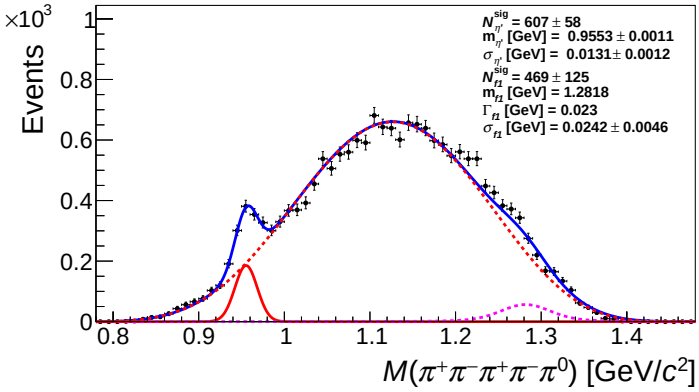
The η/ω peaks are nicely visible, but η/ω ratio is different in SMASH, data, and PLUTO (based on estimated σ) used cross sections: $\eta(\to \pi^+\pi^-\pi^0)\pi^+\pi^-$: 5.57 μb, $\omega(\to \pi^+\pi^-\pi^0)\pi^+\pi^-$: 5.57 μb (from my analysis)
$2\pi^+2\pi^-\pi^0$: 20 μb, $\eta'(\to \eta\pi^+\pi^-)$: 0.3 μb, $f_1(\to \eta\pi^+\pi^-)$: 0.012 μb
Compared with SMASH: $\sigma(pp \to pp\eta[\to \pi^+\pi^-\pi^0]\pi^+\pi^-) = 9.7$ μb; $\sigma(pp \to pp\omega\pi^+\pi^-) = 0.05$;
$\sigma(pp \to pp\eta' \to \pi^+\pi^-\eta(\to \pi^+\pi^-\pi 0)) = 11$ μb.

Sim pluto chanels, scaled $\mathcal{L} \cdot \sigma / N^{\text{evts}}$

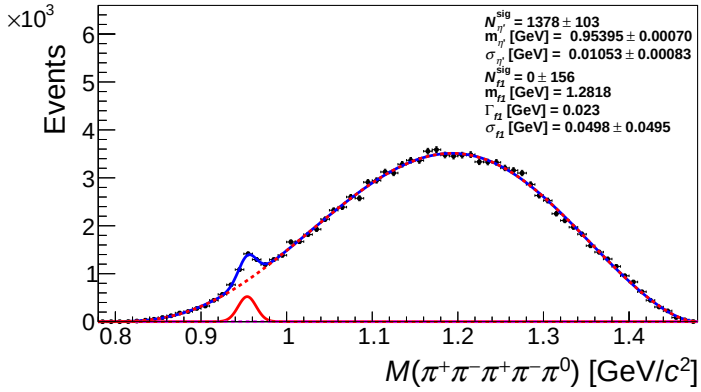
Data $\pi^+\pi^-\pi^+\pi^-\pi^0$ mass: Voigt

cut on $|m_{\pi^+\pi^-\pi^0} - m_\eta| \leq 25$ MeV, Voigt fit for $f_1(1285)$ with natural width $\Gamma = 23$ MeV

HADES



FT



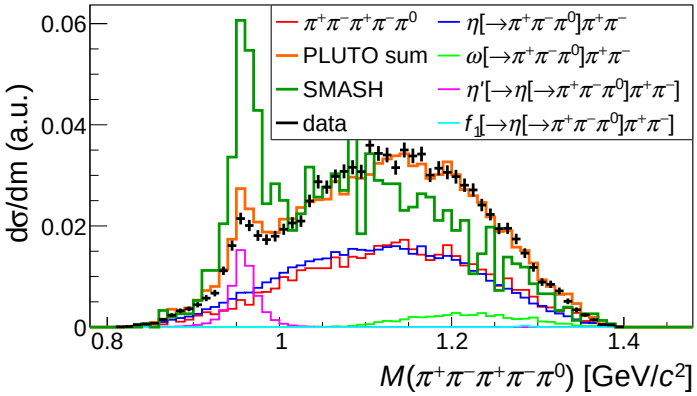
Clear η' observation, but the $f_1(1285)$ fit is inconclusive due to potential overfitting from the flexible 9th-order polynomial background.

Signal η' peak: gaussian (natural width $\Gamma = 0.23$ MeV $\ll \sigma \approx 10$ MeV), background: 9 order polynomial

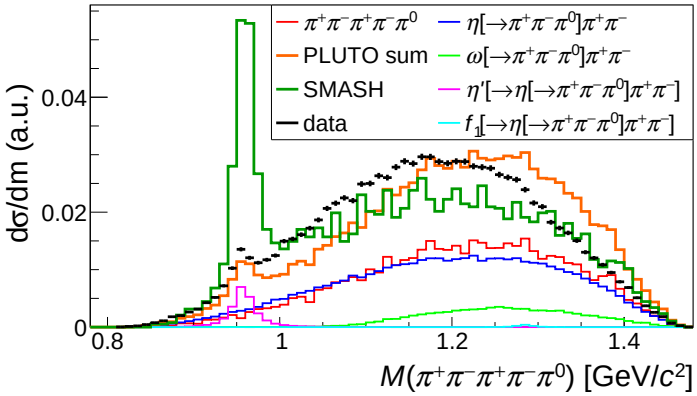
$\pi^+\pi^-\pi^+\pi^-\pi^0$ mass: data-sim

cut on $|m_{\pi^+\pi^-\pi^0} - m_\eta| \leq 25$ MeV

HADES



FT



used cross sections: $\eta\pi^+\pi^-$: 5.57 μb, $\omega\pi^+\pi^-$: 5.57 μb (from my analysis)
$2\pi^+2\pi^-\pi^0$: 20 μb, $\eta'(\to \eta\pi^+\pi^-)$: 0.3 μb, $f_1(\to \eta\pi^+\pi^-)$: 0.012 μb

Scaled such as the integral of data, SMASH, and Pluto sum =1.

cross sections from HADES

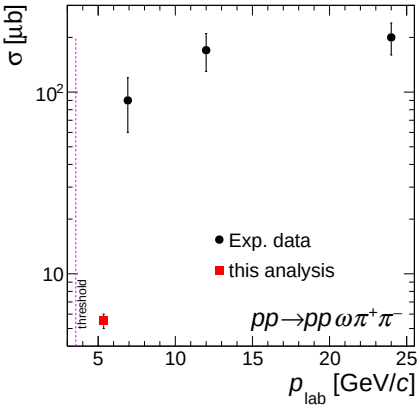
particle in final state	HADES		FT	
	events	expected counts$^{(*)}$	events	expected counts$^{(*)}$
η in $pp\pi^+\pi^-\eta(\to \pi^+\pi^-\pi^0)$	8427±30	286	37090±486	1116
ω in $pp\pi^+\pi^-\omega(\to \pi^+\pi^-\pi^0)$	3946±26	27900	33828±804	248000
η' in $pp\eta'[\to \pi^+\pi^-\eta(\to \pi^+\pi^-\pi^0)]$	607±58	1030	1378±103	1900
$f_1(1285)$		10		80

Based on this, "cross–section" could be estimated as

$$\sigma \approx \frac{N^{\text{sig}}}{\mathcal{L}\cdot\epsilon^{MC}} = \frac{N^{\text{sig}}}{\mathcal{L}}\left[\frac{N^{\text{total sim}}}{N^{\text{rec}}}\right]^{\text{MC}}$$

$pp \to ppX$ channel	σ (μb)$^{(*)}$	HADES	FT
$\eta[\to \pi^+\pi^-\pi^0]\pi^+\pi^-$	0.18	5.27 ± 0.27	5.99 ± 0.32
$\omega[\to \pi^+\pi^-\pi^0]\pi^+\pi^-$	80	5.67 ± 0.30	5.46 ± 0.31
$\eta'[\eta[\to \pi^+\pi^-\pi^0]\pi^+\pi^-]$	0.3	0.18 ± 0.02	0.22 ± 0.02

SMASH: $\sigma(pp \to pp\eta[\to \pi^+\pi^-\pi^0]\pi^+\pi^-) = 9.7$ μb; $\sigma(pp \to pp\omega\pi^+\pi^-) = 0$; $\sigma(pp \to pp\eta') = 11$ μb.

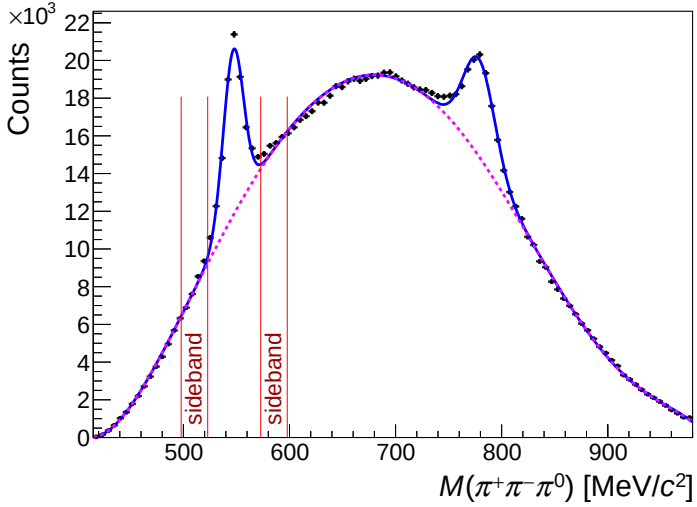


$^{(*)}$ see slides 3–5; if channel is mentioned with decay mode, *e.g.* $\eta[\to \pi^+\pi^-\pi^0]$, the branching ratio factor is included

Sideband subtraction

Sideband subtraction in for 5π analysis:

- for subsequent analysis – 5π inv. mass with η' peak expected, prepare two histograms: with cut on 3π inv mass $m_\eta \pm 25$ MeV - under signal peak, and so-called sidebands: $25 < |m_{\pi^+\pi^-\pi^0} - m_\eta| < 50$ MeV.
- Based on fit, calculate background yields under peak and in sidebands.
- subtract from the signal ($|m_{\pi^+\pi^-\pi^0} - m_\eta| \leq 25$ MeV) the sideband 5π inv. mass distribution, scaled by the ratio of the yields background yields under peak and in sidebands.

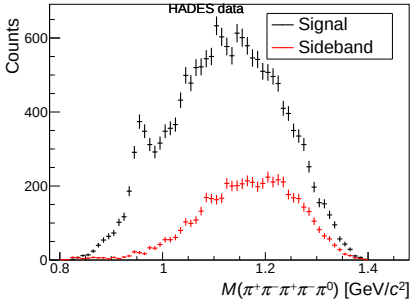


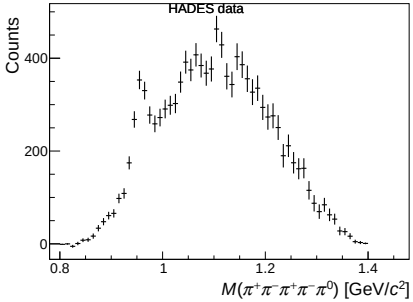
The 3π inv. mass contains 4 entries per event, the signal – if one of the pairs passes m_η cut; sideband – if one of the pairs is in sideband but not in signal

Data $\pi^+\pi^-\pi^+\pi^-\pi^0$ mass: Sideband subtraction

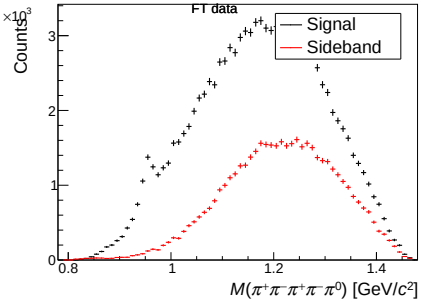
$\pi^+\pi^-\pi^0$ pairs selection cut on $|m_{\pi^+\pi^-\pi^0} - m_\eta| < 30$ MeV, before (*top*), after (*bottom*) sideband subtraction.

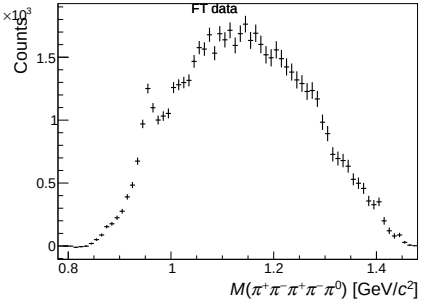
HADES





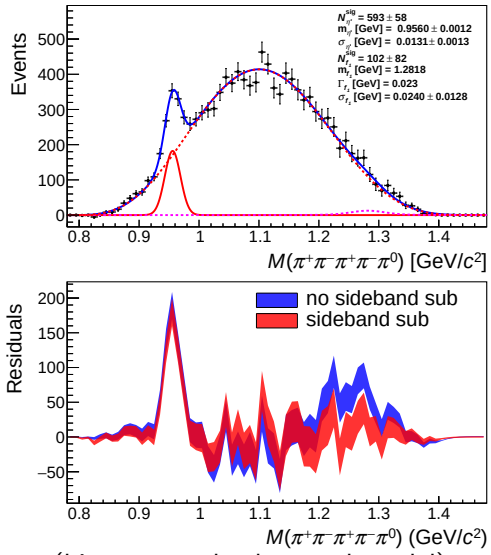
FT



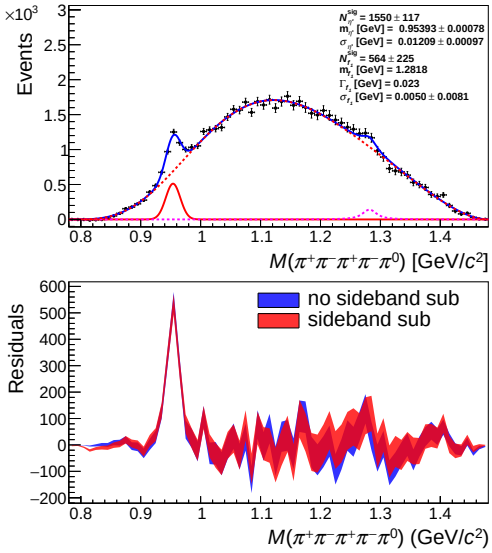


Data $\pi^+\pi^-\pi^+\pi^-\pi^0$ mass: Sideband subtraction and Fit

HADES



FT



Residuals are: (histogram - background model)

The η' fit is comparable with previous (without sb. subtraction): 607 ± 58 (*HADES*), 1378 ± 103 (*FT*)

The f_1 signal is within 2σ consistent with zero. chi2/ndf = 0.9314 (*HADES*), 1.3370 (*FT*); "no sideband subtraction" – see slide 17

Upper limit estimation of f_1 cross section

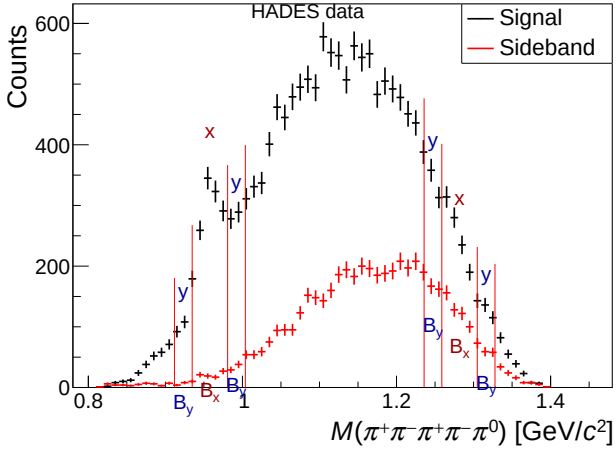
Upper limit estimation of f_1 cross section by likelihood ratio test:
Poisson distribution of background and known efficiency (ratio between background events in signal and background region):
x – events in the signal region (η': $\pm$20 MeV; f_1: $\pm$23 MeV),
y – events in the background region (η': $\pm 20 \ldots 40$ MeV; f_1: $\pm 23 \ldots 46$ MeV;),
Bx – number of side band background events in the signal region,
By – number of side band background events in the background region,

	x	y	Bx	By	95% Limits
HADES η'	1675	1257	123	143	[494, 694]
HADES f_1	1475	1453	741	709	[0, 65]
FT η'	6840	5779	740	882	[1787, 2196]
FT f_1	15006	14357	8364	8119	[0, 557]

Counts:

particle	HADES		FT	
	events	95% CL	events	95% CL
η'	607$\pm$58	[494,694]	1378$\pm$103	[1787,2196]
$f_1(1285)$	102 ± 82	[0, 65]	564 ± 225	[0,557]

The 95% CL estimation for the η' cross section is:
Case H: $\sigma = 0.14 \ldots 0.20$ μb, **Case FT**: $\sigma = 0.28 \ldots 0.34$ μb
(Expected $\sigma = 0.3$ μb)
The 95% CL upper limit estimation for the $f_1(1285)$ cross section is:
Case H: $\sigma =$ **78 nb**, **Case FT**: $\sigma =$ **83 nb** (Expected $\sigma = 12$ nb)



Syst uncertainty contributions

- Luminosity syst. uncrt: L = 5660.6, 226.0 (norm) , 180.0 (sys) $\Rightarrow \sqrt{226^2 + 180^2}/5660.6 \approx 5\%$.
- Kin fit prob cut: p=0.05 $\rightarrow$ p=0.1
- PID: $\pm 2.5\sigma \rightarrow \pm 1\sigma$; $\pm 3\sigma$
- 3π signal selection: $m_\eta \pm 25$ MeV $\rightarrow$ 20, 30 MeV
- Sideband subtraction: $m_\eta \pm 25$ MeV $\rightarrow$ 20, 30 MeV
- 3π , 5π bkg parametrization: 9 $\rightarrow$ 7, 11-th order polynomial

total syst uncertainty: sum of max deviations in quadrature

$pp \rightarrow ppX$ channel	$\eta[\rightarrow \pi^+\pi^-\pi^0]\pi^+\pi^-$	$\omega[\rightarrow \pi^+\pi^-\pi^0]\pi^+\pi^-$	$\eta'[\eta[\rightarrow \pi^+\pi^-\pi^0]\pi^+\pi^-]$
Luminosity	5	5	5
Kin fit prob cut	1	2	3
PID	10	9	16
eta sig selection	3	5	8
3π bkg param	5	6	10
sideband sub			12
5π bkg param			10
total syst [%]	11	12	25

...under investigation...

Conclusions & TODO

- First-try estimations of exclusive $\eta\pi^+\pi^-$ and $\omega\pi^+\pi^-$ and η' cross sections were conducted – with η' is in consistent with expectation. Extracted η' signal (after sidebands subtraction) in HADES and FT follows our estimates (fit to data $\sigma(pp \to pp\eta') = 3 \pm 0.6$ μb, model [1]: $2.28 - 2.69$ μb):

$pp \to ppX$ channel	this analysis (μb)	SMASH μb
$pp \to pp\eta\pi^+\pi^-$	24 ± 0.1 (stat.) ± 3 (syst.)	42
$pp \to pp\omega\pi^+\pi^-$	6.2 ± 0.1 (stat.) ± 0.8 (syst.)	0.05
$pp \to pp\eta'$	2 ± 0.2 (stat.) ± 0.5 (syst.)	11

- f_1 meson search is not yet conclusive with fit results
- The 95% CL upper limit estimation of f_1 cross section via likelihood ratio test (TRolke method) for the $f_1(1285)$ cross section is:
  Case H: $\sigma =$ **78 nb**, **Case FT**: $\sigma =$ **83 nb** (Expected $\sigma = 12$ nb)
  $\Rightarrow$ higher sensitivity needed to more accurately test the model.

TODO:

- Efficiency and acceptance correction
- $2p$, $\geq 1\pi^+$, $\geq 1\pi^-$, missing η mass
- angular distribution and Dalitz plots for η'
- publication

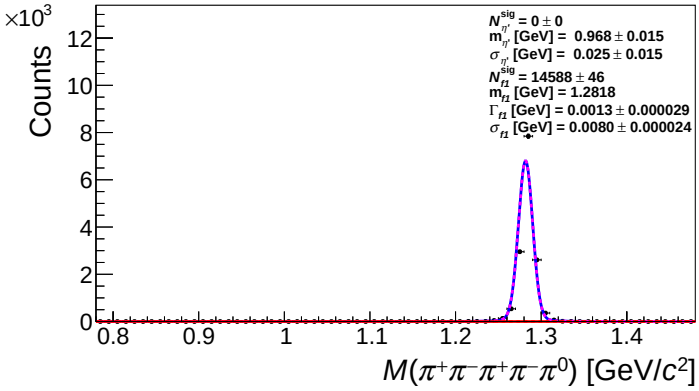
[1] From effective Langrangian $\{\pi, \rho, \eta\}NN^*$ couplings P. Lebiedowicz, Workshop 1GeV Scale (2024)

Backup Slides

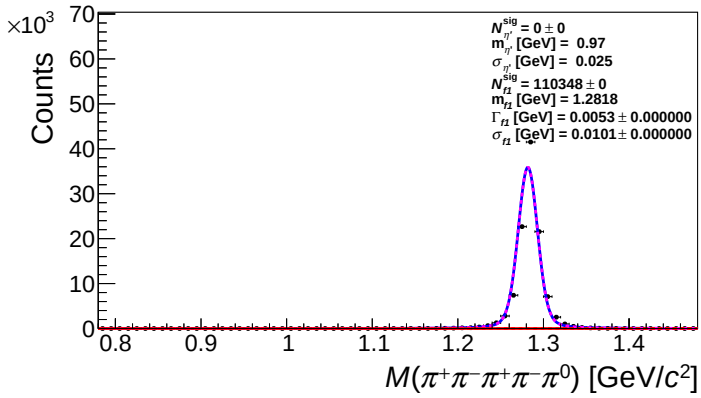
PLUTO f_1 channel: $\pi^+\pi^-\pi^+\pi^-\pi^0$ mass: Voigt

$\pi^+\pi^-\pi^0$ pairs selection: cut on $|m_{\pi^+\pi^-\pi^0} - m_\eta| \leq 25$ MeV

Hades



FT



Natural width of 23 MeV (not yet? present in PLUTO) is order of detector resolution ≈10 MeV

RooFit: **extended** maximum likelihood fits

Let $P(m)$ be the probability density function of the invariant mass m variable:

$$P(m) = \frac{N_{\text{sig}} S(m) + N_{\text{bkg}} B(m)}{N_{\text{sig}} + N_{\text{bkg}}},$$

PDFs $S(m)$ and $B(m)$ are normalized.
The fit is the maximization of the likelihood function defined as
binned:

$$\mathcal{L} = \text{Poisson}\left(N | N_{\text{sig}} + N_{\text{bkg}}\right) \cdot \prod_{h_i} \text{Poisson}\left(h_i | \int_{h_i} \left[N_{\text{sig}} S(m) + N_{\text{bkg}} B(m)\right] dm\right),$$

unbinned:

$$\mathcal{L} = \text{Poisson}\left(N | N_{\text{sig}} + N_{\text{bkg}}\right) \cdot \prod_{m} P(m)$$

where $\text{Poisson}(N|\lambda)$ is the Poisson distribution probability function with mean λ, and the product is conducted over (binned) histogram bins with content h_i, or (unbinned) N data entries.
If fit is not **extended**, $N \equiv N_{\text{sig}} + N_{\text{bkg}}$.

Comparison of event selection: only 2pi- 2pi+; best RK χ^2

		Nevents	η	ω	η'
HADES	$= 2\pi^-, = 2\pi^+$	30461	773 +/- 12	372 +/- 14	569 +/- 51
	$\geq 2\pi^-, \geq 2\pi^+$, best RK χ^2	30689	7668 +/- 115	3636 +/- 115	569 +/- 52
	ratio	30689	7668 +/- 115	3636 +/- 115	569 +/- 52
FT	$= 2\pi^-, = 2\pi^+$	273629	35991 +/- 170	33243 +/- 185	1369 +/- 143
	$\geq 2\pi^-, \geq 2\pi^+$, best RK χ^2	276505	35693 +/- 174	32337 +/- 186	1404 +/- 144
	ratio	0.9896	7668 +/- 115	3636 +/- 115	569 +/- 52

TRolke (Method 4: Poisson Bkg, Known Eff)

Let a probability model for the data is given by:
$X \sim \text{Poisson}(\mu + b)$, $Y \sim \text{Poisson}(\tau b)$,
where μ is the signal rate, b is the background rate, and τ is fixed (e.g. from MC or sidebands)

NIMPR A 551, 2-3, p. 493-503.